

Simultaneous constraints on cosmology and photometric redshift bias from weak lensing and galaxy clustering

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ABSTRACT

We investigate the expected cosmological constraints from a combination of cosmic shear and large-scale galaxy clustering using realistic photometric redshift distributions. Introducing a systematic bias in the lensing distributions (of 0.05 in redshift) produces a $>2\sigma$ bias in the recovered matter power spectrum amplitude and dark energy equation of state for preliminary Stage III surveys. We demonstrate that cosmological error can be largely removed by marginalizing over biases in the assumed weak-lensing redshift distributions. Furthermore, the cosmological constraining power is retained despite removing much of the information on the lensing redshift biases. This finding relies upon high-quality redshift estimates for the clustering sample, but does not require spectroscopy. All galaxies in this analysis can thus be assumed to come from a single photometric survey. We show that this internal constraint on redshift biases arises from complementary degeneracy directions between cosmic shear and the combination of galaxy clustering and shear–density cross-correlations. Finally we examine a case where the assumed redshift distributions differ from the truth by more than a simple uniform bias. We find that the effectiveness of this self-calibration method will depend on the survey details and the nature of the uncertainties on the estimated redshift distributions.

Key words: gravitational lensing: weak – galaxies: statistics – cosmology: observations – dark energy – dark matter – large-scale structure of Universe.

1 INTRODUCTION

Cosmic shear is potentially the most powerful tool available to cosmologists today. As an unbiased probe of the mass distribution, it offers powerful constraints on the mean density of the Universe and the clustering of dark matter. It is also expected to shed new light on the late-time accelerated expansion of the Universe and thus measure the dark energy equation of state and test general relativity on the largest scales. A three-decade programme aiming to extract unprecedented constraints on our cosmological model from cosmic shear is now midway to completion. It began soon after the first detection in 2000 (Bacon, Réfrégier & Ellis 2000; van Waerbeke et al. 2000; Wittman et al. 2000; Kaiser, Wilson & Luppino 2000) using $\sim 10\,000$ galaxies and will culminate in catalogues of more than a billion galaxies by the end of the coming decade (Stage IV, Albrecht et al. 2006). Logarithmically, we are halfway there, with ongoing analyses of the preliminary Stage III data sets

containing ~ 10 M galaxies (DES Collaboration 2015; Hildebrandt et al. 2016, see also Heymans et al. 2013; Jee et al. 2016). The increase in the number of galaxies with reliable shape measurements has allowed tighter cosmology constraints, but also requires better control of systematic biases. In this Letter, we focus on a potential Achilles’ heel of galaxy imaging surveys for cosmology: the use of photometric redshifts (photo- z) to estimate distances to galaxies. Tomographic cosmic shear analyses bring a number of benefits (Hu 1999), but place stringent requirements on our knowledge of galaxy redshift distributions. Amara & Réfrégier (2007), Abdalla et al. (2008) and Jouvel et al. (2009) present detailed studies of the spectroscopic follow-up needed for Stage IV, while Ma, Hu & Huterer (2006), Huterer et al. (2006) and Bernstein (2009) use numerical forecasts to explore cosmological impact of photo- z biases. Many others (e.g. Bordoloi et al. 2012; Cunha et al. 2014) present detailed studies of specific photo- z systematics, albeit with less focus on the ultimate cosmology.

Tightening systematics requirements have sparked interest in spatial cross-correlations between photometric and spectroscopic galaxies within the survey volume as a method for calibrating

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photo- z (Newman 2008; Ménard et al. 2013; de Putter, Doré & Das 2014; Choi et al. 2015). Given the limited amount of spectroscopic information available, several authors have speculated about calibrating redshift error from the imaging survey itself. Huterer et al. (2006) show that cosmic shear alone affords a limited capacity for self-calibration. Schneider et al. (2006) and Sun, Zhan & Tao (2015) investigate the photo- z calibration information available from Stage IV galaxy clustering, and Zhan (2006) explores the constraining power on w_0 using a similar technique with cosmic shear plus clustering constraints. Zhang, Pen & Bernstein (2010) point out that shear–density cross-correlations (between shear and galaxy counts, also referred to as tangential shear or galaxy–galaxy lensing) can help to constrain photo- z error when combined with galaxy clustering.

All the studies mentioned above make a crucial assumption, which is unlikely to be realized in practice, that the galaxies used for cosmic shear have a systematics-correctable galaxy clustering signal. In practice, regions of the sky with better (worse) seeing conditions are likely to contain a higher (lower) number density of galaxies usable for cosmic shear (e.g. see appendix C of Choi et al. 2015). A large spurious clustering signal will arise as a result, rendering standard galaxy clustering analyses useless. Thus, in practice, there is usually a different galaxy sample selection for the shear and clustering samples. This is widely accepted in galaxy–galaxy lensing studies and was also the case in the first combined cosmic shear plus large-scale structure analysis with real data (Nicola, Réfrégier & Amara 2016), and was considered for Stage IV in the forecasts of Krause & Eifler (2016). Though one has twice as many redshift distributions to understand as in a shear-only analysis, this offers an opportunity: we can choose a galaxy clustering sample with well-controlled photo- z , which in turn helps to calibrate the redshift distribution of the weak-lensing sample. In this Letter, we explore the potential for simultaneously constraining photo- z error and cosmology using cosmic shear, galaxy clustering and shear–density cross-correlations. Unlike previous studies we consider a scenario in which the redshift distribution of the shear catalogue and galaxy clustering catalogues differs significantly. We assume the clustering sample is highly homogeneous and dominated by luminous red galaxies, which yield high-quality photo- z .

This Letter is structured as follows. Section 2 outlines our analysis with a description of the simulated data vectors, redshift distributions and the photo- z uncertainties considered. In Section 3, we investigate the power of these data to internally constrain photo- z biases. Finally, a series of robustness tests are presented to explore the limits of this effect. We adopt a fiducial flat Λ CDM cosmology with $\sigma_8 = 0.82$, $\Omega_m = 0.32$, $h = 0.67$, $w_0 = -1$ and $\Omega_b = 0.049$.

2 METHODOLOGY AND ASSUMPTIONS

We follow a method similar to Joachimi & Bridle (2010) (see also Duncan et al. 2014 for a similar analysis) to implement a forecast of the three weak-lensing plus large-scale structure 2-point functions: cosmic shear, galaxy clustering and shear–density cross-correlations. We carry out a Markov Chain Monte Carlo (MCMC) forecast by simulating a data vector and covariance at a fiducial cosmology, then fitting a series of trial cosmologies and computing the likelihood of each. The fiducial data vector in Fig. 1 contains three types of correlation, each with 25 logarithmically spaced top hat bins over $10 < \ell < 3000$. We use COSMOSIS (Zuntz et al. 2015) to MCMC sample parameter space and compute matter power spectra using CAMB (Lewis, Challinor & Lasenby 2000) with non-linear corrections from Takahashi et al. (2012).

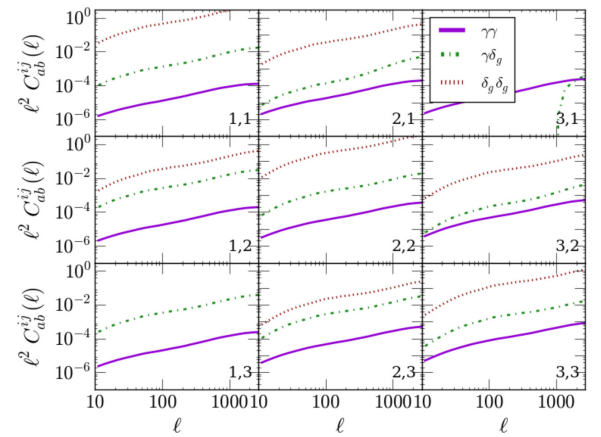


Figure 1. Components of the fiducial data vector. Shown are angular power spectra of cosmic shear (purple solid), galaxy clustering (red dotted) and the cross-correlations (green dot-dashed). Each panel corresponds to a unique redshift bin pairing. In the panels, where it is not visible, the $\delta_g\delta_g$ spectrum is below the range shown. All values shown are positive, apart from $C_{\gamma\delta_g}^{1,3}$ (upper right), which becomes negative and is smaller than the lowest point on this scale at $\ell < 900$.

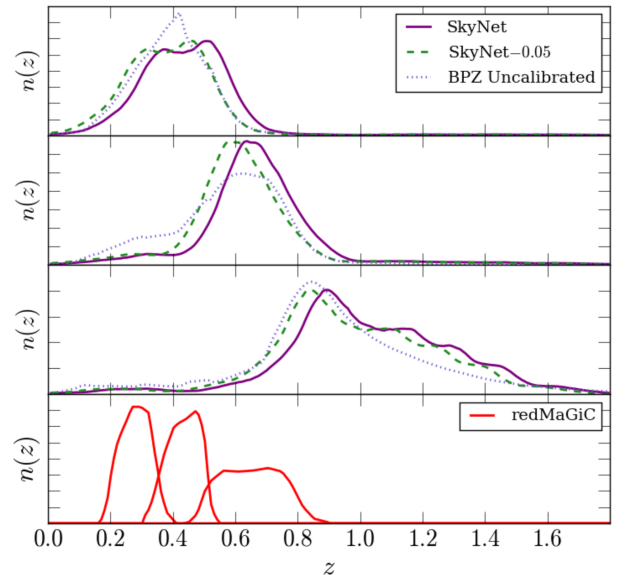


Figure 2. Redshift distributions considered. The upper panels show the shear $n(z)$ s, taken from DES SV (Bonnert et al. 2015): SKYNET (solid purple; fiducial), SKYNET with a 0.05 bias (dashed green), and BPZ (dotted blue) without the shift of 0.05 in redshift used in Bonnett et al. (2015). The lower panel displays the galaxy density catalogue, DES SV redMaGiC (Rozo et al. 2016) in bins defined by Clampitt et al. (2016).

The fiducial analysis assumes a galaxy catalogue typical of a preliminary Stage III survey. We use the galaxy number density of the Dark Energy Survey Science Verification (DES SV; 6.8 arcmin⁻²; Jarvis et al. 2015), with $\sigma_\epsilon = 0.2$ and an area of 1500 sq. deg. This gives 37M galaxies, which is a little larger than or comparable to the Canada-France Hawaii Telescope Lensing Survey (CFHTLenS)¹ and the Kilo-Degree Survey (KiDS)², DES³ and Hyper-Suprime Cam (HSC)⁴ preliminary analyses. We use the SKYNET $n(z)$

¹ <http://www.cfhtlens.org>

² <http://kids.strw.leidenuniv.nl>

³ <http://www.darkenergysurvey.org>

⁴ <http://www.naoj.org/Projects/HSC>

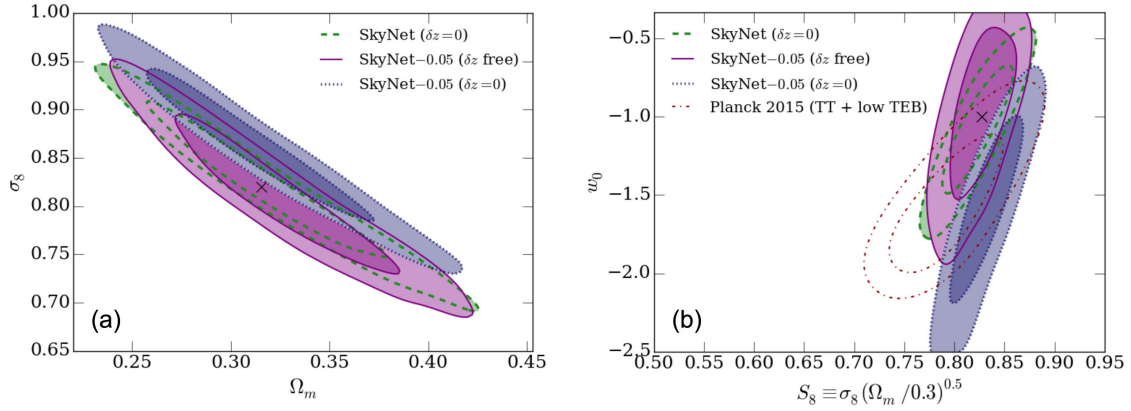


Figure 3. (a) Forecast constraints on the matter density and clustering amplitude in Λ CDM and (b) dark energy equation of state in w CDM for various assumptions about photo- z . For reference Planck 2015 constraints (temperature + low-frequency polarization; Planck Collaboration et al. 2015) are shown in red (dot-dashed). The colours in each panel indicate three photo- z scenarios. In green are the results of using the SKYNET $n(z)$ in the theory calculation and fixing $\delta z = 0$. We show this as an unrepresentative ideal case, where the photometric estimates provide a perfect representation of the true galaxy distribution. Overlain are the same, but using SKYNET biased downwards by 0.05 in redshift under the (erroneous) assumption of no bias (blue dotted) and varying three δz^i nuisance parameters marginalized with a Gaussian prior of width $\Delta\delta z = 0.1$ (purple solid). The input cosmology is shown by the black cross.

presented in Bonnett et al. (2015) (shown in Fig. 2 above), as used in the DES SV shear analysis, and marginalize over multiplicative shear bias with a Gaussian prior ($\Delta m = 0.02$) (see also Jarvis et al. 2015; Fenech Conti et al. 2016; Jee et al. 2016). For conservatism we model intrinsic alignments (IA) using the non-linear alignment model (Bridle & King 2007) with an additional power law in redshift (e.g. Joachimi et al. 2011; DES Collaboration 2015), and unlike previous analyses allow the amplitude and power-law index to differ for GI and II. This gives four IA parameters.

To model a realistic galaxy clustering catalogue, the $n(z)$ of the DES SV redMaGiC luminous red galaxy catalogue (Rozo et al. 2016; Clampitt et al. 2016) is adopted. A linear galaxy bias is applied in each bin and marginalized with a wide flat prior. To avoid the non-linear bias regime, we impose conservative scale cuts to the clustering sample and discard information below a scale determined by rescaling the prescription of Rassat et al. (2008). We tune this rescaling approximately to match the smallest scales found by Kwan et al. (2016) to be unaffected non-linear bias. This leads to a factor of 3 increase over the Rassat et al. (2008) cuts, giving $\ell_{\max} = (91, 203, 432)$ for each bin, respectively.

Redshift distribution error is parametrized by δz^i , which describes a uniform linear translation, $\tilde{n}^i(z) = n^i(z + \delta z^i)$. For the galaxy clustering sample we marginalize over δz^i with a Gaussian prior of standard deviation $\Delta\delta z^i = 0.01$. The photo- z for the shear catalogue is somewhat lower in quality due to the number and type of objects required for shear measurement, and for the fiducial analysis we apply a conservative Gaussian prior ($\Delta\delta z^i = 0.1$). In addition to the nuisance parameters described above, we vary five cosmological parameters with no external priors. The fiducial analysis then has 21 degrees of freedom, $\mathbf{p} = (\sigma_8, \Omega_m, h, \Omega_b, n_s, A_{\text{GI}}, A_{\text{II}}, \eta_{\text{GI}}, \eta_{\text{II}}, m^i, \delta z^i, b_g^i, \delta z^i)$.

3 SIMULTANEOUS CONSTRAINTS ON COSMOLOGY AND PHOTOMETRIC REDSHIFT BIAS

Fig. 3(a) shows constraints on the matter density Ω_m and clustering amplitude σ_8 for various assumptions about the shear photo- z uncertainties. The green dashed lines are from the fiducial analysis assuming the shear redshift distributions are known precisely ($\Delta\delta z^i = 0$). We investigate the effect of using an incorrect redshift

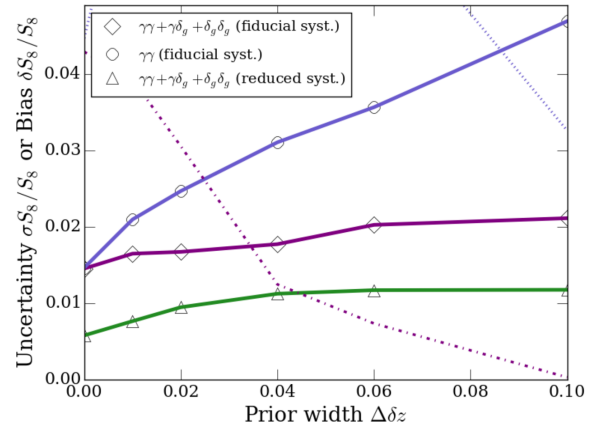


Figure 4. Uncertainty σS_8 on $S_8 \equiv \sigma_8(\Omega_m/0.31)^{0.5}$ for different prior widths $\Delta\delta z$. Blue circles show cosmic shear alone and purple diamonds indicate shear, galaxy clustering and cross-correlations. The green triangles also show the latter combination, but assuming intrinsic alignments and multiplicative shear calibration are known perfectly. In the first two cases, we also show the bias δS_8 induced by marginalizing with an erroneously zero centred prior of width $\Delta\delta z$ (dotted and dot-dashed).

distribution in the simulation, expanding on a similar technique developed in Bonnett et al. (2015). A bias of 0.05 in redshift is applied to $n(z)$ in the simulated data vector, a value inspired by the calibration applied to BPZ in Bonnett et al. (2015) to match simulations, but we assume the redshift distributions are known perfectly. The result (blue dotted, Fig. 3a) is now incompatible with the true cosmology at greater than 95 per cent confidence. Finally, we allow freedom in the value of the photo- z biases δz^i , marginalizing with the fiducial prior ($\Delta\delta z^i = 0.1$). The purple solid contours are shifted back close to the true input cosmology, despite the erroneous redshift distributions. The width of the purple contours is not greatly degraded relative to the case where the distributions are perfectly known (green dashed and blue dotted); we find a degradation in error on S_8 of 40 per cent. For Fig. 3(b) we carry out the same calculation as in Fig. 3(a), but additionally vary the dark energy equation of state w_0 . Qualitatively similar results are obtained.

In Fig. 4, we investigate in more detail how the prior width $\Delta\delta z^i$ on the redshift distribution bias δz^i affects the uncertainty on S_8 . We contrast the results from cosmic shear alone (blue) with

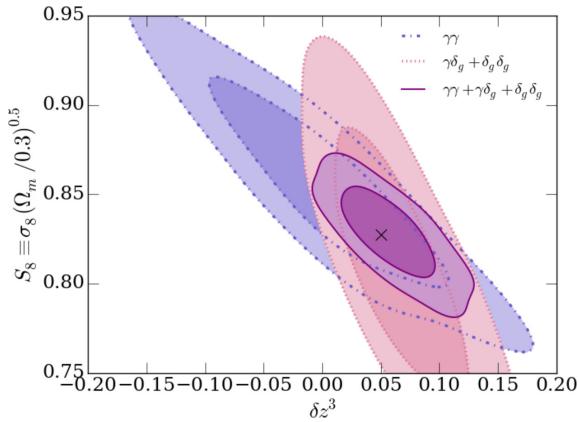


Figure 5. Degeneracies between photo- z bias in the uppermost redshift bin (δz^3) and cosmology (S_8) for cosmic shear alone (blue dash-dot), galaxy clustering and shear-density cross-correlations (pink dotted), and the combination (purple solid). The input parameters are shown by the black cross.

those from the combination of cosmic shear, galaxy clustering and shear-density cross-correlations (purple). We show results using our fiducial systematics assumptions (purple) and using less conservative assumptions (no multiplicative shear or IA uncertainty; green). We see that cosmic shear alone cannot self-calibrate photo- z uncertainties, whereas the combination with galaxy clustering and shear-density correlations weakens the sensitivity of the constraint to prior width, for both fiducial and optimistic systematics. S_8 is significantly biased (δS_8) at all values of $\Delta \delta z^i$ for cosmic shear (dotted lines) and is biased very little by $\Delta \delta z^i = 0.1$ for the combination of data sets (dot-dashed).

Fig. 5 gives some insight into how the self-calibration works, using the biased redshift distribution (SKYNET -0.05) as an illustration. The blue (dot-dashed) contours show the degeneracy between cosmology and photo- z uncertainties from cosmic shear alone. The contours are closed because we have applied a conservative prior on photo- z uncertainties ($\Delta \delta z^i = 0.1$). In the absence of additional information the cosmology constraints from cosmic shear will be biased because the prior on δz^i is centred on zero whereas the truth is at $\delta z^i = 0.05$. The galaxy clustering and shear-density cross-correlations constrain a different degenerate combination of cosmology and redshift bias (pink dotted). Thus when these three 2-point functions are combined, they produce the purple (solid) contours, which are now centred close to the true cosmology and offer much tighter constraints on cosmology and photo- z uncertainties than either cosmic shear alone or galaxy clustering plus shear-density correlations alone. In physical terms, Fig. 5 demonstrates how a tight constraint on the clustering redshift distributions constrains the lensing sample. Since we are correlating each of our biased lensing kernels with well-known $n(z)$ s in multiple clustering bins, the combination of the $\gamma \delta_g$ and $\delta_g \delta_g$ correlations contain enough information to constrain the angular diameter distance to each lensing bin (and thus δz). The $\gamma \gamma$ correlations are then freed to further constrain cosmology.

We investigate the robustness of these results to perturbing the fiducial assumptions and calculate the degradation $D \equiv \sigma_{S_8}(\Delta \delta z = 0.1) / \sigma_{S_8}(\Delta \delta z = 0) - 1 = 40$ per cent for the fiducial analysis. We characterize stochastic bias in the relation between mass and light with a scale-independent parameter per redshift bin $r_g^j \equiv C_{GG}^{ij} / C_{GG}^{ij}$ (see e.g. Dekel & Lahav 1999; Joachimi & Bridle 2010). We find that the three extra free parameters, $|r_g^j| < 6$, make little difference ($D = 45$ per cent), but increase $\sigma_{S_8}(0)$ by 6 per cent relative to the fiducial case. We next marginalize over an additional

photo- z uncertainty parameter per bin, which stretches the redshift distributions $\tilde{n}^i(z) = n^i(z + S_z^i[z - z_p])$, where z_p is the peak in bin i . The cosmology constraint is weakened at all δz , which reduces the relative degradation slightly ($D = 28$ per cent). A similar reduction ($D = 24$ per cent) occurs if ℓ_{\max} is increased by a factor of 3. We also rerun our analysis using a wide prior on the shear measurement bias ($\Delta m = 0.05$) and find $D = 16$ per cent, due to a ~ 72 per cent degradation in the error on S_8 , independent of $\Delta \delta z^i$. The biggest impact arises when we use a conservative value for the prior on the photo- z uncertainties of the density sample ($\Delta \delta z^i = 0.05$), which gives a factor of 2 degradation ($D = 103$ per cent), with $\sigma_{S_8}(0.1)$ and $\sigma_{S_8}(0)$ increased by 75 and 6 per cent, respectively, relative to fiducial. In all instances considered, we find no significant residual bias δS_8 when δz^i are marginalized.

To test the self-calibration result in a situation where the true redshift distribution differs from the assumed $n(z)$ by more than a simple bias, we take the DES SV redshift distributions from an alternative code (BPZ). Of the SV codes, BPZ was the most discrepant with our fiducial choice (SKYNET). To provide a relatively stringent test we choose not to apply a 0.05 calibration used in DES SV. Fig. 6 shows the result. By construction the green contours in Figs 3 and 6 are identical and use the fiducial $n(z)$ in the simulation and the fit. The blue contours use the qualitatively different BPZ $n(z)$ in the simulation, but assume perfect photo- z ($\delta z = 0$ and $\Delta \delta z^i = 0$) in the fit. Unlike in Fig. 3, marginalizing over photo- z bias ($\Delta \delta z^i = 0.1$) no longer trivially moves the contours (solid purple) on to the input cosmology (cross). This suggests a uniform bias in redshift may not always sufficiently account for differences between the true and estimated distributions, depending on the survey specifications. Finally, we repeat the fiducial BPZ analysis twice, once fixing IA parameters and once additionally varying S_z , but find no qualitative change in the residual bias. In the case of BPZ, the truth is within the 68 per cent confidence contour, but a more detailed investigation is necessary to account for the possible range of redshift errors.

4 CONCLUSION

We investigate the potential for current galaxy imaging surveys to self-calibrate photo- z distribution uncertainties, for the first time considering the case in which the shear sample is different from the galaxy clustering sample and has substantial calibration uncertainties. We focus on a preliminary Stage III data set with ~ 40 M galaxies, in which the galaxy clustering sample has well-understood photo- z ($\Delta \delta z^i = 0.01$). We find that the combination of cosmic shear, galaxy clustering and shear-density cross-correlations is much more robust to errors and uncertainties in the redshift distribution calibration than cosmic shear alone. The uncertainty on $S_8 \equiv \sigma_8(\Omega_m/0.31)^{0.5}$ is increased by only 40 per cent on marginalizing over three free independent bias parameters with prior $\Delta \delta z^i = 0.1$, relative to the case $\Delta \delta z^i = 0$. This contrasts with more than a factor of 2 degradation for cosmic shear alone. We illustrate that this is because cosmic shear constrains a different degenerate combination of cosmology and photo- z calibration parameters to clustering and shear-density cross-correlations. We find that the combination of all three 2-point functions can correct even a substantial bias (of 0.05) in the $n(z)$ to accurately recover the input cosmology. This result is robust to a basic stochastic bias parameter and strengthened by less conservative scale cuts in the galaxy clustering analysis. We note two crucial differences between our results and established methods: (i) we do not rely on spectroscopic data, allowing a self-contained analysis of a single photometric survey and (ii) we do

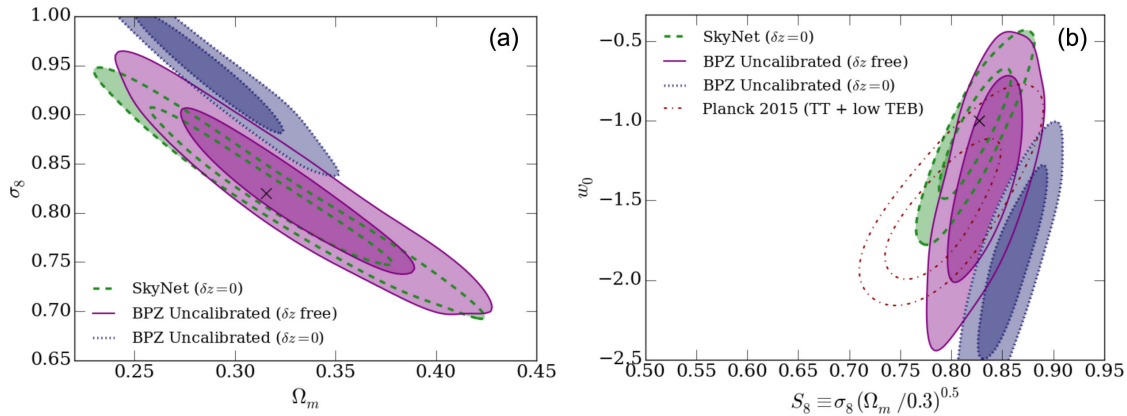


Figure 6. Same as Fig. 3 but now using a more realistic realization of the discrepancy between the estimated and true galaxy redshift distributions. Here we use the $n^i(z)$ from an alternative photo- z code (BPZ) in the simulated data vector and the $n^i(z)$ of the fiducial photo- z code (SkyNet) in the fit.

not require well-matched samples in redshift coverage, so the clustering catalogue can be significantly shallower. The self-calibration result is weakened if redshift bias in the clustering sample is poorly controlled ($\Delta\delta z^i = 0.05$). Using an alternative $n(z)$ estimate (BPZ) we demonstrate that this result may change if the deviation of the $n(z)$ from the truth is not fully captured by a uniform translation. By inspection of the distributions, we can see that the most prominent qualitative differences arise from secondary peaks or outliers. Unfortunately, such errors vary between photo- z methods and cannot be characterized analytically for a generic implementation. In practice, the validity of our findings should be verified for specific realizations of the photo- z error. We note, however, that the uncalibrated BPZ results fail basic photo- z requirements, even for Stage III surveys. They should thus be considered as an extreme case and not a realistic prediction of photo- z performance for Stage IV.

This investigation advances on most previous numerical forecasts in implementing MCMC sampling rather than Fisher analyses and assumes a low-density clustering sample with relatively well-known redshifts. We do, however, assume Gaussian covariance matrices, which tend to underestimate the uncertainties for cosmic shear and could thus make our forecasts overoptimistic. Investigation of non-Gaussian covariances is beyond the scope of this Letter. We also assume the Limber approximation holds on the scales used and ignore redshift-space distortions. The results suggest that self-calibration may be a practical solution for current cosmological surveys, assuming reliable photo- z can be obtained for the galaxy clustering catalogue if the weak-lensing redshift distributions cannot be easily calibrated via a different route.

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